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# Distributed learning, extremum seeking, and model-free optimization for the resilient coordination of multi-agent adversarial groups

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**14. ABSTRACT**
This proposal focuses on the analysis and design of coordination algorithms for multiple agents deployed in adversarial environments. The multi-agent systems can represent miscellaneous autonomous and semi-autonomous vehicles that are remotely controlled by operators. These groups can be subject to attacks from other external agents leading to complex networked adversarial settings.
The proposal presents work in two main areas: 1) the use of a class of receding-horizon type of algorithms to overcome the effect of a type of uncoordinated attackers on a multi-vehicle-operator group, and 2) the use of extremum seeking (ES) techniques to learn Nash equilibria in finitely- and infinitely-many player noncooperative games and to solve high-dimensional optimization problems. Extensions and applications of these techniques were developed during the realization of the project.

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**Final Report on AFOSR grant FA09550-12-1-0183**

## Abstract:

This research effort belongs to the general area of distributed learning, and the control and coordination of multiple and single agent systems, and is led by Dr. Martinez and Dr. Krstic at UC San Diego. The work has particular impact on the development of a theory of autonomy science, which accounts for both the aspects of resilience under adversaries, and learning via extremum seeking, and distributed optimization techniques. During this period, several theoretical advancements as well as applications have been carried out, which are summarized as follows.

## Research Results:

**Dr. Martinez's** effort focuses on the analysis and design of robust (multi-)agent coordination algorithms subject to failure and adversarial action. The agents can represent miscellaneous autonomous and semi-autonomous vehicles that are remotely controlled by operators. These groups can be subject to attacks from other external agents leading to complex networked adversarial settings. Attacks and malicious actions considered include Denial-of-Service (DoS), replay, and man in the middle attacks, eavesdropping and privacy violation, and, more recently, virus spreading. In addition to this, work to advance the state of the art in multi-agent systems has been continued.

## Technical Results:

1. *A set of novel algorithms based on receding-horizon control and distributed parameter learning for the robust coordination of multi-agent systems.* A study of the tradeoffs in costs/effort of the algorithms under the following set of assumptions have been considered: (a) unknown adversaries introducing on/off disturbances to the system (e.g. denial of service), (b) partially known adversary, which modifies the control commands to a certain extent; however, the operator can exploit this model to learn the adversary, (c) the adversarial action aims to reconstruct the whole multi-agent system objective and control commands.
2. *Novel time-triggered, event-triggered, and receding-horizon-based control laws for remote system operation under DoS pulse-width modulated systems*. By means of parameter tuning that learns the characteristics of the DoS signal, event-triggering and time-triggering controls for a linear system are derived.
3. *Privacy preserving coordination algorithms for multi-agent systems.* Consensus algorithms that do not require agents to exchange state information, but secondary variables which do not allow for the reconstruction of the agents' states by an eavesdropping agent, are devised.
4. *Robust coordination (consensus) of multi-agent systems when these are subject to outlier measurements.* This is based on dynamic consensus algorithms combined

with RANSAC, which is a 'voting strategy' widely used in computer vision and that allows to deal with more than 50% outliers.

5. *Coordination (consensus and distributed optimization) of multi-agent systems using event-triggered control.* We studied problems of dynamic average consensus and a class of unconstrained continuous-time optimization algorithms for the coordination of multiple agents.
6. *Virus spreading mitigation distributed optimization algorithms over computer/robotic networks.* We have produced a variety of discrete-time and distributed optimization algorithms that can be used by a multi-operator group to decide on an optimal resource allocation subject to constraints and eradicate a virus spreading over a network. These algorithms have various robust features (such as robustness to initialization.)

We mention the following work under review, on subjects that are more related to the general topics of distributed learning, and optimization, in GPS denied environments:

1. *Distributed and discrete-time convex optimization algorithms subject for unknown cost functions.* This work, which is to appear, is similar to simultaneous perturbation stochastic approximation (SPSA), but based on recent theory of stochastic hybrid systems, and building on the discrete-time optimization algorithms of (6.) above. Thus, it does not have the limitations of SPSA such as diminishing step sizes.
2. *Control of single agents in GPS denied environments with obstacles but via an adaptation of the SPSA techniques.* Similar techniques as above can be applied for a wheeled-robot to reach the maximum of a convex cost function using projections to handle obstacles.

We report 33 publications refereed publications resulting from the grant for the period of performance; see the file 'publications-afosr.pdf' for more information.

Over the period of this grant, Co-PI **Dr. Krstic** has achieved several advances in extremum seeking described as follows:

**Applications:**

1. Extremum seeking has been established as one of the powerful methodologies for navigating autonomous vehicles in GPS-denied environments and several publications are reported below where advances in "source seeking" for single vehicles and groups of vehicles are presented. For example, an application to GPS-denied swarms of autonomous vehicles has been developed using stochastic extremum seeking, where the vehicles, starting from *distinct* and arbitrary positions, congregate to the source, while being fed a common (*indistinct*) control input.
2. Maximization of UAV endurance via using air turbulence with extremum seekings is also achieved in one of the publications below. Extremum seeking has

also been demonstrated on maximum power point tracking for photovoltaic arrays and for wind turbines.

3. ES has recently been implemented on the Mars Rover Curiosity and, as of May 2015, is used for the focusing of the ChemCam instrument which performs chemical testing of rocks at a distance by shining a laser beam, vaporizing, the rock surface, and focusing the reflection using a mirror back to a camera, with the help of extremum seeking, with the image subsequently being used in the chemical analysis of the rock.
4. Extremum seeking has also been implemented as the enabling technology in extreme ultraviolet light sources on ASML-Cymer silicon wafer scanners. This technology reduces the feature sizes of transistors on microchips by 4-10 times compared to previous technologies. Eight such units, at the price of $100 million per unit, have been delivered to semiconductor fabs in Taiwan and China and running since 2014.
5. Extremum seeking has also been implemented on a kilometer-long accelerator at the Los Alamos National Laboratory for optimizing the high voltage converter modulator.

**Theory:** A number of theoretical advances in extremum seeking are reported in the publications listed below.

1. Extensions from deterministic to stochastic extremum seeking in several papers and one book.
2. Extension of ES from single-agent optimization to non-cooperative games in which the payoff functions are unknown to the players. ES performs the optimization of the players' strategies with a guaranteed convergence to the Nash equilibrium strategies.
3. Extension from gradient-like to Newton-like optimization strategies.
4. Development of ES algorithms for batch-to-batch optimization of open-loop finite-horizon optimal control strategies (which has been applied to lasers and in charged particle accelerators).
5. Development of model-free feedback algorithms for stabilization of nonlinear systems using the application of ES with candidate control Lyapunov functions.

**Dr. Krstic** reports about 50 peer-reviewed publications resulting from the grant for the period of performance. See the file 'publications-afors.pdf' for more information.

Next we give recognitions earned by Martinez and Krstic during this period.

**AWARDS AND HONORS (Dr. Martinez)**

CAREER PROMOTIONS AND RECOGNITIONS

2014 Full Professor, UC San Diego
2016 Senior Editor, IEEE Transactions on Control of Networked Systems

AWARDS TO STUDENTS

2011 *Minghui Zhu,* 2011 MAE Outstanding Graduate Student of the Year award, now an Assistant Professor at Penn State University

2013 *Solmaz S. Kia*, UC Presidential Fellowship recipient, now an Assistant Professor at UC Irvine

2015 *Andres Cortes,* 2015 MAE Outstanding Graduate Student of the Year award, now an Assistant Professor at Penn State University, now at EPRI

## KEYNOTE LECTURES

2016 Keynote Speaker at the "*Workshop on Control and Observability of Network Dynamics,"* Mathematical Biosciences Institute, Ohio State University, April 2016

2016 Keynote Speaker at the "*1st So-Cal Robotics Symposium,"* Mathematical Biosciences Institute, Ohio State University, April 2016

2013 Keynote Speaker at the "*1st Workshop on Wireless Intelligent Sensor Networks (WISeNet),"* Duke University, 2013

2012 Plenary Speaker at the "*3rd IFAC Workshop on Distributed Estimation and Control of Networked Systems"* (NECSYS), Santa Barbara, 2012

## AWARDS AND HONORS (Dr. Krstic)

CAREER RECOGNITIONS

2015 Foreign Member, *Academy of Engineering of Serbia*

2015 ASME DSCD *Nyquist Lecture Prize*

2015 Fellow of *SIAM* (Society for Industrial and Applied Mathematics)

2015 Associate Fellow of *AIAA* (American Institute for Aeronautics and Astronautics)

2014 Fellow of *ASME* (American Society of Mechanical Engineers)

2014 Fellow of *IET* (Institution of Engineering and Technology, UK)

OTHER MAJOR RECOGNITIONS

2016 *Qian Ren* Professor, Northeastern University, China

2015 Invitation Fellow, *Japan Society for the Promotion of Science*

2015 Honorary Professor, Dalian Maritime University, Donghua University, Chongqing University, Northeastern University, China

2013 Distinguished Visiting Fellow of the *Royal Academy of Engineering*, United Kingdom

BOOK PRIZE

2014 Harold Chestnut Textbook Prize, IFAC (International Federation for Automatic Control), triennial prize—the highest recognition for authoring a book in the field of control systems

AWARDS TO STUDENTS

2014 *Chancellor's Dissertation Medal* in Engineering (among 150 PhDs granted in 2013), UCSD, *Nikolaos Bekiaris-Liberis*

2014 *Best European Dissertation in Control* of Complex and Heterogeneous Systems, European Embedded Control Institute (EECI), *Delphine Bresch-Pietri*

2013 *Best University-wide Dissertation Award, Paris-Tech* (includes 12 most prestigious and oldest technical and business universities in the Paris region such as Ecole des

Mines, Ecole Polytechnique, ENSAE, etc.), *Delphine Bresch-Pietri*

**KEYNOTE LECTURES**

2015 *ASME Dynamic Systems and Control Conference, Nyquist Lecture*, Columbus, OH
2015 *IFAC Workshop on Adv. Control and Navigation for Autonomous Aerospace Vehicles*, Sevilla, Spain
2014 *IEEE Conference on Decision and Control*, Los Angeles
2013 *Congreso Nacional de Control Automático*, Mexico
2013 *IFAC Workshop on Control of Systems Governed by Partial Diff. Equations*, Paris
2013 *IFAC Nonlinear Control Systems Symposium (NOLCOS)*, Toulouse, France
2013 *IFAC Workshop on Adaptation and Learning in Control and Signal Proc.*, Caen, France
2013 *IEEE Workshop on Open Problems and Challenges in Automotive Control*, Washington DC
2012 *IEEE Conference on Industrial Electronics and Applications*, Singapore
2012 *IEEE International Conference on Mechatronics and Automation*, Chengdu, China

**FELICITATION LECTURES**

2016 *Coron* Fest, UPMC, Sorbonne Universités, Paris
2015 *Praly* Fest, Ecole des Mines, Paris
2012 *Spong* Fest, University of Texas, Dallas
2012 *Sontag* Fest, Rutgers University
2012 *Bastin* Fest, Université Catholique de Louvain, Belgium

# Publication List related to award FA09550-12-1-0183

Sonia Martínez

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**Books**

(JP1) M. Zhu and S. Martínez. *Distributed Optimization-Based Control of Multi-Agent Networks in Complex Environments*. Springer-Briefs in Electrical and Computer Engineering. 2015

**Journal papers**

(JP-1) M. Zhu and S. Martínez. On distributed constrained formation control in operator-vehicle adversarial networks. *Automatica*, 49(12):3571–3582, 2013

(JP-2) M. Zhu and S. Martínez. On the performance analysis of resilient networked control systems under replay attacks. *IEEE Transactions on Automatic Control*, 59(3):804–808, 2014

(JP-3) M. Zhu and S. Martínez. On attack-resilient distributed formation control in operator-vehicle networks. *SIAM Journal on Control and Optimization*, 52(5):3176–3202, 2014

(JP-4) S. S. Kia, J. Cortés, and S. Martínez. Dynamic average consensus under limited control authority and privacy requirements. *International Journal on Robust and Nonlinear Control*, 25(13):1941–1966, 2015

(JP-5) E. Montijano, J.I. Montijano, C. Sagüés, and S. Martínez. Robust discrete-time dynamic average consensus. *Automatica*, 50(12):3131–3138, 2014

(JP-6) E. Montijano, S. Martínez, and C. Sagués. Distributed robust consensus using RANSAC and dynamic opinions. *IEEE Transactions on Control Systems Technology*, 23(1):150–163, 2015

(JP-7) S. S. Kia, J. Cortés, and S. Martínez. Distributed convex optimization via continuous time coordination algorithms with discrete-time communication. *Automatica*, 55:254–264, 2015

(JP-8) S. S. Kia, J. Cortés, and S. Martínez. Distributed event-triggered communication for dynamic average consensus in networked systems. *Automatica*, 59:112–119, 2015

(JP-9) H. Shisheh Foroush and S. Martínez. On triggering control of single-input linear systems under pulse-width modulated DoS jamming attacks. *SIAM Journal on Control and Optimization*, 2016. Subject to minor revision

(JP-10) E. Ramírez and S. Martínez. A distributed nonlinear dynamics for virus spread control. *Automatica*, 2016. To appear

(JP-11) E. Ramírez and S. Martínez. Distributed and robust fair optimization applied to virus diffusion control. *IEEE Transactions on Network Science and Engineering*, 2016. Under review

(JP-12) E. Ramírez and S. Martínez. Distributed discrete-time optimization algorithms with application to resource allocation in epidemics control. *Optimal Control Applications and Methods*, 2016. Under review

**Conference proceedings**

(CP-1) M. Zhu and S. Martínez. Attack-resilient distributed formation control via online adaptation. In *IEEE Int. Conf. on Decision and Control and European Control Conference*, pages 6624–6629, Orlando, FL, USA, December 2011

(CP-2) M. Zhu and S. Martínez. Attack-resilient distributed formation control via online adaptation. In *IEEE Int. Conf. on Decision and Control*, pages 6624–6629, Orlando, FL, USA, December 2011

(CP-3) M. Zhu and S. Martínez. Stackelberg game analysis of correlated attacks in cyber-physical system. In *American Control Conference*, pages 4063–4068, June 2011

(CP-4) M. Zhu and S. Martínez. Attack-resilient distributed formation control via online adaptation. In *IEEE Int. Conf. on Decision and Control and European Control Conference*, pages 6624–6629, Orlando, Florida, December 2011

(CP-5) H. Shisheh Foroush and S. Martínez. On event-triggered control of linear systems under periodic Denial of Service attacks. In *IEEE Int. Conf. on Decision and Control*, pages 2551–2556, Maui, HI, USA, December 2012

(CP-6) M. Zhu and S. Martínez. On distributed resilient consensus against replay attacks in adversarial networks. In *American Control Conference*, pages 3553–3558, Montreal, Canada, 2012

(CP-7) H. Shisheh Foroush and S. Martínez. On multi-input controllable linear systems under unknown periodic DoS jamming attacks. In *SIAM Conference on Control and Its Applications (CT)*, pages 222–229, San Diego, CA, January 2013

(CP-8) S.S. Kia, J. Cortés, and S. Martínez. Saturation-tolerant average consensus with controllable rates of convergence. In *SIAM Conference on Control and Its Applications (CT)*, pages 121–128, San Diego, CA, January 2013

(CP-9) S. S. Kia, J. Cortés, and S. Martínez. Periodic and event-triggered communication for distributed continuous-time convex optimization. In *American Control Conference*, pages 5010–5015, Portland, OR, 2014

(CP-10) S. S. Kia, J. Cortés, and S. Martínez. Dynamic average consensus with distributed event-triggered communication. In *IEEE Int. Conf. on Decision and Control*, pages 890–895, Los Angeles, CA, USA, December 2014

(CP-11) E. Montijano, J. I. Montijano, C. Sagués, and S. Martínez. Step-size analysis in discrete-time dynamic average consensus. In *American Control Conference*, pages 5127–5132, Portland, OR, June 2014

(CP-12) H. Shisheh Foroush and S. Martínez. On the robustness of event-based synchronization under switching interactions. In *IEEE Int. Conf. on Decision and Control*, pages 2001–2006, Los Angeles, CA, USA, December 2014

(CP-13) E. Ramírez and S. Martínez. A distributed algorithm for virus spread minimization. In *American Control Conference*, pages 184–189, Portland, OR, USA, June 2014

(CP-14) E. Ramírez and S. Martínez. Distributed and robust fair resource allocation applied to virus spread minimization. In *American Control Conference*, pages 1065–1070, Chicago, IL, USA, July 2015

(CP-15) E. Ramírez and S. Martínez. Distributed stopping criteria for the power iteration applied to virus mitigation. In *Asilomar Conference on Signals, Systems, and Computers*, pages 1328–1332, Pacific Grove, CA, November 2015

(CP-16) E. Ramírez and S. Martínez. Distributed and robust resource allocation algorithms for multi-agent systems via discrete-time iterations. In *IEEE Int. Conf. on Decision and Control*, pages 1390–1395, Osaka, Japan, December 2015

(CP-17) E. Ramírez and S. Martínez. Gradient-free distributed resource allocation via simultaneous perturbation stochastic approximation. In *Allerton Conf. on Communications, Control and Computing*, Monticello, IL, USA, September 2016. To appear

(CP-18) E. Ramírez and S. Martínez. Constrained source seeking for mobile robots via stochastic approximation. In *IEEE Int. Conf. on Decision and Control*, Las Vegas, NV, USA, December 2016. To appear

**Invited book chapters**

(BC-1) M. Zhu and S. Martínez. *Cyber-security for industrial control systems: from the viewpoint of close-loop*, chapter 9: Distributed resilient control of operator-vehicle networks under cyber attacks. CRC Press, Taylor and Francis, 2016

(BC-2) H. Shisheh Foroush and S. Martínez. *Principles of Cyber Physical Systems*, chapter On triggering control techniques for cyber-physical systems. Cambridge University Press, 2016

## Publications by Co-PI Miroslav Krstic under the period of the grant

We report next about 50 peer-reviewed publications resulting from the grant for the period of performance.

**Books**

1. S.-J. Liu and M. Krstic, *Stochastic Averaging and Stochastic Extremum Seeking*, Springer, 2012.
2. N. Bekiaris-Liberis, *Nonlinear Control Under Nonconstant Delays*, SIAM, 2013.
3. I. Karafyllis and M. Krstic, *Predictor Feedback for Delay Systems: Implementations and Approximations*, Springer, 2016.

**Journal Papers**

1. N. Ghods and M. Krstic, ``Multiagent deployment over a source,'' *IEEE Transactions on Control Systems Technology*, vol. 20, pp. 277-285, 2012.
2. P. Frihauf, M. Krstic, and T. Basar, ``Nash equilibrium seeking in non-cooperative games,'' *IEEE Transactions on Automatic Control*, vol. 57, pp. 1192-1207, 2012.
3. B. Ren, P. Frihauf, R. Rafac, and M. Krstic, ``Laser pulse shaping via extremum seeking,'' *Control Engineering Practice*, vol. 20, pp. 678-683, 2012.
4. A. Ghaffari, M. Krstic, and D. Nesic, ``Multivariable Newton-based extremum seeking,'' *Automatica*, vol. 48, pp. 1759-1767, 2012.
5. J. Krieger and M. Krstic, ``Aircraft endurance maximization at medium Mach numbers by extremum seeking,'' *AIAA Journal of Guidance, Control, and Dynamics*, vol. 36, pp. 390-403, 2013.
6. A. Scheinker and M. Krstic, ``Maximum-seeking for CLFs: Universal semiglobally stabilizing feedback under unknown control directions,'' *IEEE Transactions on Automatic Control*, vol. 58, pp. 1107-1122, 2013.
7. P. Frihauf, M. Krstic, and T. Basar, "Finite-horizon LQ control for unknown discrete-time linear systems via extremum seeking," *European Journal of Control*, vol. 19, pp. 399-407, 2013.
8. A. Scheinker, M. Bland, M. Krstic, and J. Audia, "Rise-time optimization of accelerator high voltage converter modulator by extremum seeking," *IEEE Transactions on Control Systems Technology*, vol. 22, pp. 34-43, 2014.
9. A. Scheinker and M. Krstic, "Non-$C^2$ Lie bracket averaging for non-smooth extremum seekers," *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 136, paper 011010, 2014.
10. A. Scheinker and M. Krstic, "Extremum seeking with bounded update rates," *Systems and Control Letters*, vol. 63, pp. 25-31, 2014.
11. A. Ghaffari, M. Krstic, and S. Seshagiri, "Extremum seeking for wind and solar energy applications," *Dynamic Systems and Control*, vol. 2, pp. 13-21, 2014.
12. S.-J. Liu and M. Krstic, "Newton-based stochastic extremum seeking," *Automatica*, vol. 50, pp. 952-961, 2014.

13. P. Frihauf, S.-J. Liu, and M. Krstic, "A single forward-velocity control signal for stochastic source seeking with multiple nonholonomic vehicles," *ASME Journal of Dynamic Systems, Measurement, and Control*, paper 051024, 2014.
14. A. Ghaffari, M. Krstic, and S. Seshagiri, "Power optimization for photovoltaic micro-converters using multivariable Newton-based extremum seeking," *IEEE Transactions on Control Systems Technology*, vol. 22, pp. 2141-2149, 2014.
15. A. Ghaffari, M. Krstic, and S. Seshagiri, "Power optimization and control in wind energy conversion systems using extremum seeking," *IEEE Transactions on Control Systems Technology*, vol. 22, pp. 1684-1695, 2014.
16. A. Ghaffari, S. Seshagiri, and M. Krstic, "Multivariable maximum power point tracking for photovoltaic micro-converters using extremum seeking," *Control Engineering Practice*, vol. 35, pp. 83-91, 2015.
17. H.-B. Durr, M. Krstic, A. Scheinker, and C. Ebenbauer, "Singularly perturbed Lie bracket approximation," *IEEE Transactions on Automatic Control*, vol. 60, 3287-3292, 2015.
18. S.-J. Liu and M. Krstic, "Stochastic averaging in discrete time and its applications to extremum seeking," *IEEE Transactions on Automatic Control*, vol. 61, pp. 190-102, 2016.
19. S. Z. Khong, D. Nesic, and M. Krstic, "A non-model based extremum seeking approach to iterative learning control," *Automatica*.
20. T. R. Oliveira, M. Krstic, and D. Tsubakino, "Extremum seeking for static maps with delays," *IEEE Transactions on Automatic Control*.
21. A. Raisch and M. Krstic, "Overshoot-free steering-based source seeking," *IEEE Transactions on Control Systems Technology*.

**Refereed Conference Papers**

1. Scheinker, M. Krstic, "A Universal Extremum Seeking-based Stabilizer for Unknown LTV Systems with Unknown Control Directions,'' *American Control Conference*, 2012.
2. Ghaffari, S. Seshagiri, M. Krstic, "Power Optimization for Photovoltaic Micro-Converters using Multivariable Gradient-Based Extremum-Seeking,'' *American Control Conference*, 2012.
3. A. Ghaffari, S. Seshagiri, M. Krstic, "High-fidelity photovoltaic array modeling for advanced MPPT design," *2012 IEEE Canadian Conference on Electrical and Computer Engineering*.
4. Ghaffari, S. Seshagiri, M. Krstic, "High-fidelity DC-DC converter modeling for advanced MPPT design," *2012 IEEE Canadian Conference on Electrical and Computer Engineering*.
5. S.-J. Liu, P. Frihauf, and M. Krstic, "Stochastic source seeking with tuning of forward velocity,'' *2012 Chinese Control Conference*.
6. P. Frihauf, S.-J. Liu, and M. Krstic, "Stochastic source seeking with multiple nonholonomic vehicles via a single forward-velocity control signal," *2012 ASME Dynamic Systems and Control Conference*.
7. A. Scheinker and M. Krstic, "Extremum Seeking-based Tracking for Unknown Systems with Unknown Control Directions," *Proceedings of the 2012 IEEE Conference on Decision and Control*.

8. S.-J. Liu and M. Krstic, "Newton-Based Stochastic Extremum Seeking," *Proceedings of the 2012 IEEE Conference on Decision and Control*.
9. A. Ghaffari, M. Krstic, and S. Seshagiri, "Power Optimization for Photovoltaic Micro-Converters using Multivariable Newton-Based Extremum-Seeking," *Proceedings of the 2012 IEEE Conference on Decision and Control*.
10. P. Frihauf, M. Krstic, and T. Basar, "Finite-Horizon LQ Control for Unknown Discrete-Time Systems via Extremum Seeking," *Proceedings of the 2012 IEEE Conference on Decision and Control*.
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# AFOSR Deliverables Submission Survey

Response ID:6754 Data

1.

**Report Type**

Final Report

**Primary Contact Email**

**Contact email if there is a problem with the report.**

soniamd@ucsd.edu

**Primary Contact Phone Number**

**Contact phone number if there is a problem with the report**

8588224243

**Organization / Institution name**

UC San Diego

**Grant/Contract Title**

**The full title of the funded effort.**

Distributed learning, extremum seeking, and model-free optimization for the resilient coordination of multi-agent adversarial groups

**Grant/Contract Number**

**AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".**

FA9550-12-1-0183

**Principal Investigator Name**

**The full name of the principal investigator on the grant or contract.**

Sonia Martinez

**Program Officer**

**The AFOSR Program Officer currently assigned to the award**

Frederick Leve

**Reporting Period Start Date**

07/01/2012

**Reporting Period End Date**

06/30/2016

**Abstract**

This research effort belongs to the general area of distributed learning, and the control and coordination of multiple and single agent systems. The work has particular impact on the development of a theory of autonomy science, which accounts for both the aspects of resilience under adversaries, and learning via extremum seeking, and distributed optimization techniques. During this period, several theoretical advancements as well as applications on this front have been developed, which are summarized in full detail in the Report Document file.

**Distribution Statement**

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**Archival Publications (published) during reporting period:**

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**New discoveries, inventions, or patent disclosures:**
**Do you have any discoveries, inventions, or patent disclosures to report for this period?**

No

**Please describe and include any notable dates**

**Do you plan to pursue a claim for personal or organizational intellectual property?**

**Changes in research objectives (if any):**

None

**Change in AFOSR Program Officer, if any:**

The program officer changed from Fariba Fahroo to Frederik Leve

**Extensions granted or milestones slipped, if any:**

none

**AFOSR LRIR Number**

**LRIR Title**

**Reporting Period**

**Laboratory Task Manager**

**Program Officer**

**Research Objectives**

**Technical Summary**

**Funding Summary by Cost Category (by FY, $K)**

| | Starting FY | FY+1 | FY+2 |
|---|---|---|---|
| Salary | | | |
| Equipment/Facilities | | | |
| Supplies | | | |
| Total | | | |

**Report Document**

**Report Document - Text Analysis**

**Report Document - Text Analysis**

**Appendix Documents**

## 2. Thank You

**E-mail user**

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